Test Rig Development for Dual-Fuel Combustion Characterization in Optical Constant-Volume

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Dual fuel combustion has shown significant potential in reducing emissions such as nitrogen oxides and soot. Therefore, a more in-depth understanding of the phenomena controlling dual-fuel ignition and combustion processes is required to further improve engine performance. The challenge is to design and implement an experimental test rig for a constant-volume combustion chamber that allows engine-like conditions to be reproduced as accurately as possible.

Keywords : dual-fuel, combustion, constant-volume, optical measurement, characterization, split injection, ignition delay

La combustion dual a montré un potentiel important dans la réduction des émissions tel que les oxydes d'azote et les suies. Par conséquent, une compréhension plus en profondeur des phénomènes contrôlant les processus d'allumage et de combustion dual est nécessaire pour encore améliorer le comportement du moteur. Le défi est de concevoir et mettre en œuvre un banc d'essai d'une chambre de combustion à volume constant qui permet reproduire au mieux les conditions de fonctionnement d'un moteur.

Mots-clés : combustibles dual, combustion, volume constant, mesures optiques, caractérisation, injection fractionnée, délai d'injection

1. Introduction

Dual-fuel combustion is seen as a very promising technology. In fact, it allows to couple the characteristics of two different fuels - so optimizing the combustion process in terms of fuel conversion efficiency and pollutant emission levels - eventually selectable from renewable fuels, both liquid and gaseous, so contributing to CO_2 reduction [1]. The most investigated dual-fuel combustion is the one coupling diesel fuel and methane (or natural gas which contains around 90% in volume of methane). Despite the undoubted advantages associated with this combustion, some drawbacks still remain unsolved. These are mainly engine operation during idle and low engine loads as well as engine knocking tendency at full load with high natural gas substitution rates [2].

Despite the very high number of papers concerning diesel injection in Constant-Volume Combustion Chamber [3-8] or describing the behaviour of compression ignition engines converted in order to operate in dual-fuel diesel-methane (or natural gas) combustion [9-13], only a few are available analysing the dual-fuel combustion in optically accessible engines [14-16] and very few in controlled conditions like constant-volume combustion chamber [17, 18]. On the other hand, a deeper understanding of the complex phenomena governing ignition and combustion development in dual-fuel conditions is fundamental in order to optimize charge preparation, in terms of pilot injection settings (pilot injection quantity, timing, rail pressure and multiple injections strategies), injector design (nozzle geometry, injector cone angle) and gaseous fuel supply system (fumigation, indirect or direct injection). For example, the experimental results on pilot fuel distribution, natural luminosity and chemiluminescence of OH* species shown in [14], allowed to highlight some aspects of the mechanisms governing pilot fuel autoignition and mixture combustion development. Relevant insights were at low equivalence ratios, the consumption of premixed fuel in the central part of the charge is not achieved. So possibly explaining the increase in unburned hydrocarbon emissions found by many studies in fuel-lean conditions. For higher equivalence ratios, evidence of flame propagation becoming the dominant governing factor of combustion was found. Furthermore, experimental results obtained in controlled conditions would allow the development of specific models of dual-fuel combustion behaviour, so paving the way towards combustion optimization. However, the examples of experimental facilities allowing to run experiments on dual-fuel combustion in controlled conditions are very few:

- In [17], a study concerning ignition delay of pilot injection in dual-fuel combustion was performed for a wide range of initial temperatures and pressures conditions, gas equivalence ratio and mass of pilot injection in a constant volume chamber. In this case, the chamber was heated by heating elements. However, the chamber did not have any opening allowing optical access to the combustion. Moreover, the pilot injection was performed through an in-line diesel injection pump.

- In another study [18], the installation, similar to the previous one, consisted in a chamber preheated using heating cartridges. In this case an optical opening allowed to visualize the combustion; however, the charge consisted in fully premixed methanol/air mixture ignited by a diesel injection.

Therefore, in order to understand dual-fuel (DF) combustion fundamentals in more depth, a new test rig has been designed and developed, taking into account the strengths and weaknesses of the previous rig test, developed during the previous work [19]. In a previously published paper [20], the experimental results obtained on the pilot spray development were used in order to evaluate the capability of the spray models in describing pilot spray penetration in dual-fuel conditions (low fuel amount, low-medium injection pressure). In this study, further developments of the test rig are described, thanks to which the autoignition of pilot injection and following combustion of methane/air premixed charge can be achieved.

2. Setup of the constant-volume combustion vessel

As previously mentioned, a system for the measurements is needed. It is one of the main parts of the work which has to be accurately described. It is used for all the measurements to achieve in the different conditions prescribed by the parameters we want to consider and described later as split injection and so on. We have to understand that figure 1 is a final system which has been developed and modified after the different problems which have been met. The test rig is mainly constituted by the optical constant-volume vessel, which is the central part of the picture and the different systems to measure temperatures, pressures. As well as the different valves for the different injections of the different fuel, air and exhaust. Also the necessary glow plugs to preheat the mixture and a spark plug to ignite the mixture. And the sources of fuels, here pure methane and commercial diesel (classical mixture of linear hydrocarbons from 14 C to 20).

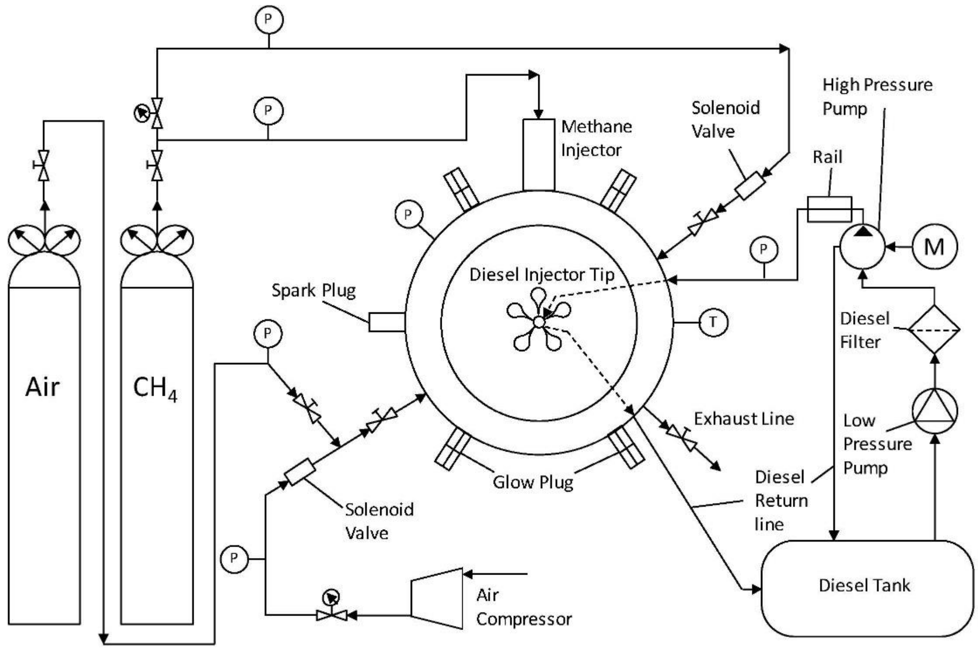

Figure 1 : schematic installation

The chamber or reactor and its main elements are presented in figure 2 with each part numbered for a description of their function. We may notice the presence of a window in order to observe the inside and to perform measurements with a camera.

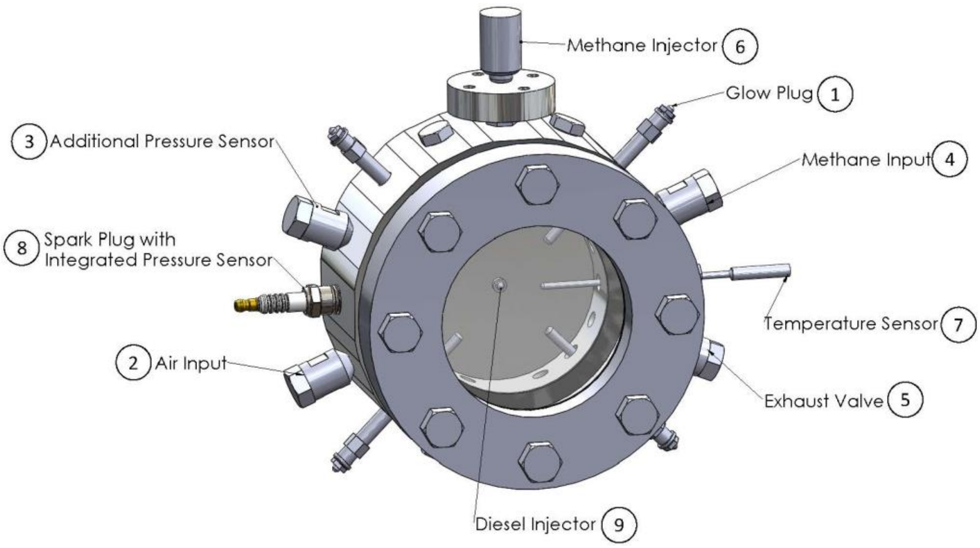

Figure 2 : Combustion chamber

This chamber is constructed of an Ergal 7075 cylinder with a useful volume of 270 cm3. This cylinder is closed with a bolted steel flange. The flange allows a glass aperture with a quartz window, which offers the visualization of the combustion. Originally the cylinder had 12 openings for introducing glow plugs (fig. 2, n° 1) but there are not all used anymore, some are closed. Four glow plugs were removed in favour of a high and low pressure compressed air inlet (fig. 2, n° 2), as well as an additional pressure sensor (fig. 2, n° 3), a methane inlet (fig. 2, n° 4) and an exhaust system (fig. 2, n° 5). This last one allows emptying the system after a combustion test and an air flow is injected to cool down the vessel. The other openings for the different devices are foreseen as the one opening being at the top for methane injector. As mentioned above, an opening for a first inlet of methane is also present in the picture (fig. 2, n° 4). There are also two openings on the side, one for the temperature sensor (fig. 2, n° 7) and the other for the spark plug and pressure sensor (fig. 2, n° 8). Finally, in the centre of the rear face, an opening is provided (foreseen) for the injection of the diesel fuel (fig. 2, n° 9). All the openings are threaded. There is also a non-opening hole underneath which allows the chamber just to be fixed firmly.

3. Experimentation

3.1. Leakage tests

To ensure the best possible sealing of the chamber, all openings must be checked, between each fitting. The pressure order in the chamber at the time of the first combustion is 30 barg. To evaluate the leaks, the chamber is set approximately at this pressure and all openings are closed. The pressure evolution over time is recovered. The experiment stops once the pressure has reached equilibrium or the evolution of the pressure variation has stabilized. Therefore, a combustion curve will be compared to the obtained leakage curve in order to observe whether the leakage is a significant factor in the pressure variation. As a general observation, the control of the leakages due to pressure up to 30 bar was considered as mastered. We can see two pressure curves in figure 3. The grey curve was obtained by the leakage test as the reference one, the black curve is the downward phase of the first combustion. The time scale chosen for the analysis is one second: it is during this time that almost all the pressure variation following combustion occurs. The grey curve keeps a relatively stable value, which makes it possible to consider that the post-combustion pressure variation comes from heat exchanges and not because leakage. We can also observe that the broken line, representing an estimation of the temperature, follows relatively closely the shape of the black pressure curve, which supports the hypothesis that heat exchanges are at the origin of almost the entire pressure drop. Therefore, despite high pressure leaks, for short duration events the leaks can be neglected and the installation can be considered as adequate for testing for this pressure range.

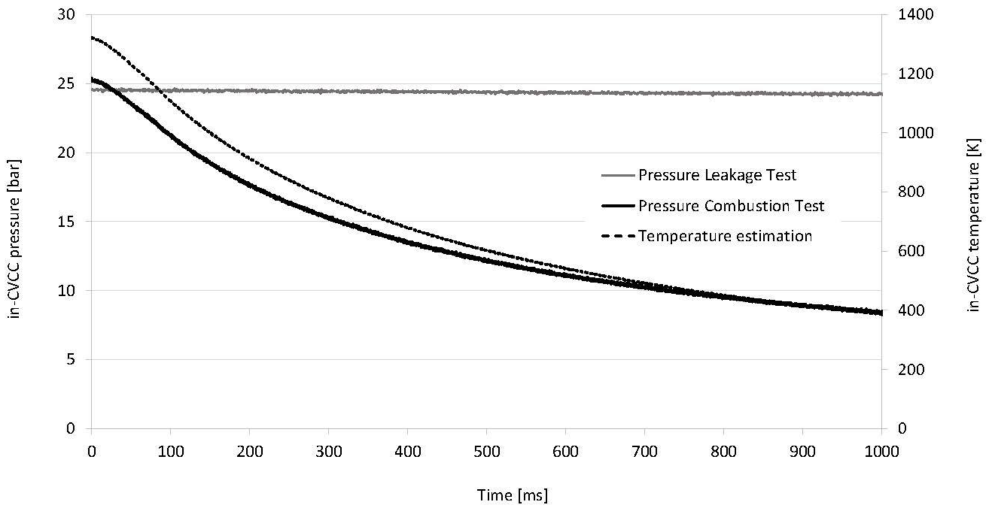

Figure 3 : Comparison of pressure losses due to leakage and leakage + heat exchange

3.2. Characterisation of methane injector

The technical data sheets and the current literature do not allow to have a precise value of the mass of methane introduced in the chamber. A series of tests were carried out to answer this question more precisely. The objective was to be able to link the pressure difference in the chamber during an injection to the number of moles of methane injected and thus the mass. To make this link, the formula of ideal gas law was used. The chamber was first filled with fresh air up to a defined value of chamber backpressure. A series of ten methane injections (with constant injection pressure) were then performed using a fixed value of injector energizing time and dwell between consecutive injections. The ten methane injections were triggered, while pressure, temperature and injection signals were recorded. The temperature inside the chamber did not show significant variations compared to the ambient temperature after ten injections, therefore the filling process was considered isothermal with very good approximation. These experiments were repeated for different levels of the controlling parameters. In particular, methane injection pressure and chamber backpressure were varied on three levels, thus realizing five values of pressure ratio. Two energizing time were also tested in order to characterize the mass variation due to injection duration. Finally, two different dwells between injections were also tested in order to identify the incidence of mass leakage on the pressure variation.

To calculate the value of the pressure difference due to an injection, the pressure before injection must be subtracted from the pressure after injection. To do this, the value of the pressure difference of the first injection is equal to the difference between the first maximum and the first minimum containing in the vector. The same applies to the following injections. As 10 injections were made to have the difference pressure average for one injection, it is enough to average the injections.

All tests were post-processed and the calculated mass introduced into the combustion chamber reported in figure 4 as a function of the injection ratios. The data were differentiated according to injection pressure and injection time. Each mark represents the average of 10 injections, the standard deviation is attached to each mark. Tests abnormally out of range were excluded in order not to distort the general trend.

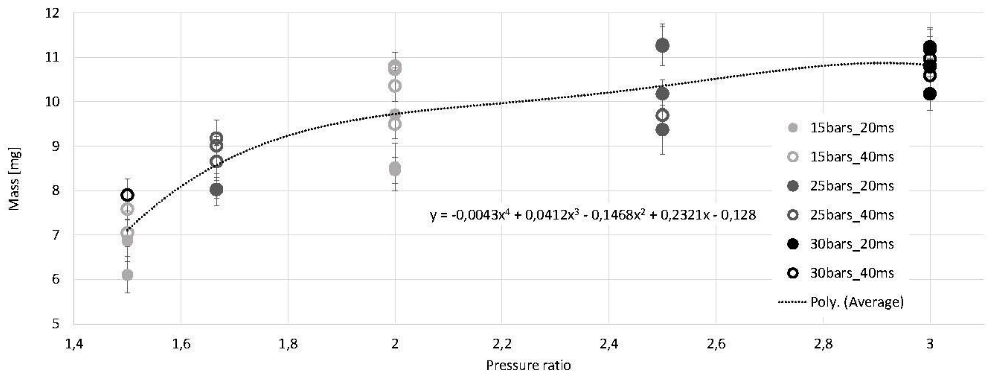

Figure 4 : Average of methane mass introduce during 20ms at different pressure ratios

To obtain a coherent set of points, the mass injected into the combustion chamber during the 40 ms injections was halved to be directly comparable to the 20 ms injections. This also shows that the injection time is directly proportional to the mass of methane injected.

Then, with the average of the injected masses for each ratio, a trend curve is plotted. The polynomial equation of degree 4 of this curve is recovered and used to have an estimate of the injected mass as a function of the opening time and the injection pressure ratio. A second degree equation should more accurately represent the physical phenomenon but, according to the results, a 4 degree trend curve allows to obtain a more realistic allure, although there is no theoretical basis behind it, it is just fitting. When the injection is done at a ratio test the equation is not used. When the injection is performed at a different pressure ratio, then it is used to obtain an estimation of the actual amount of methane introduced.

3.3. First combustion

To control the combustion of the methane-diesel-air mixture, it is important to know the initial conditions and to control them. The future objective of this part is to study the behaviour of the first combustion composed exclusively of methane and air and ignited by a spark plug. As previously specified, air and methane are introduced into the combustion chamber separately (fig. 2, n° 2 and n° 4). Furthermore, the amount of the two gaseous species have to ensure a desired final pressure and the desired air-methane ratio. This latter parameter was controlled by measuring the partial pressure related to each specie. Particular care was taken to ensure this first combustion would be reproducible. In fact, knowing and controlling the pressure variation as a function of time due the first combustion makes possible to know when to inject methane and diesel fuel for the second combustion. The pressure and consequently temperature must be high enough when the diesel fuel is injected, otherwise its auto-ignition will not occur. Moreover, the longer the time between methane and diesel fuel injection, the better the homogeneity of the methane-air mixture (100-150 ms). However, a second methane amount cannot be injected too early, or it may either burn during the first combustion or auto-ignite.

The combustion chamber is initially filled with air at atmospheric pressure. The targeted quantity of methane is introduced into the chamber using a valve. The final pressure is achieved by using compressed air from the air compressor. Once all valves are closed, the data acquisition process is activated and the spark plug trigger signal is sent. Once the data acquisition is complete, the exhaust gas valve can be opened. The air then flows through the chamber to completely renew the air contained and cool the chamber sufficiently to repeat the next test under similar conditions. The temperature condition is ambient after reaching an equilibrium (22 °C).

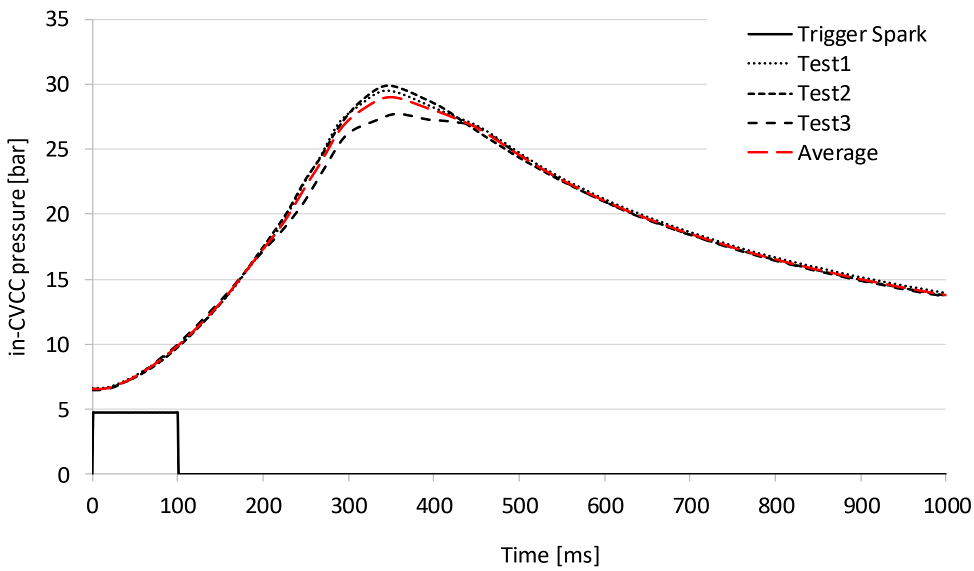

Figure 5 : λ of combustion = 1.31

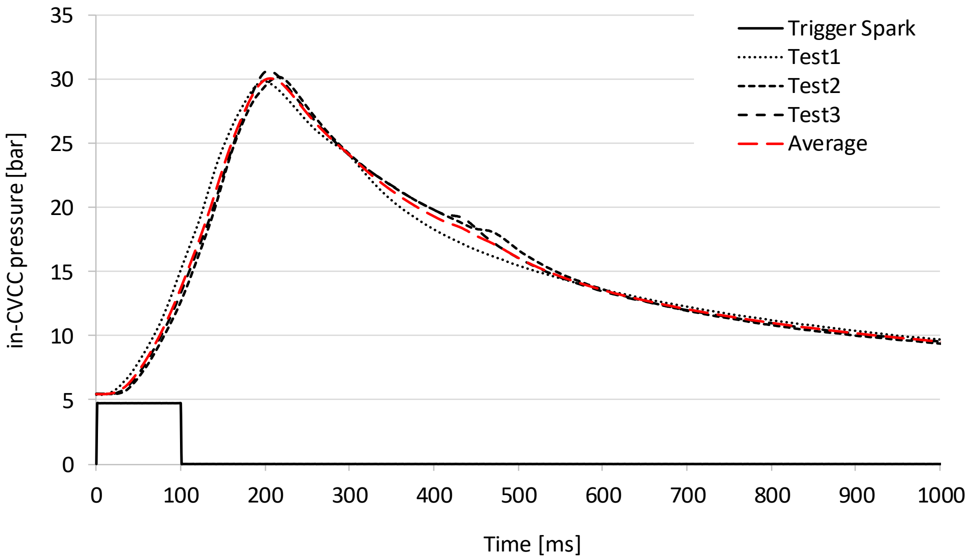

Figure 6 : λ of combustion = 1.12

It is possible to note from figures 5 and 6 that the combustion process is acceptably repeatable, for the two tested conditions. Furthermore, it can be seen that the combustion process is slower for figure 5 than figure 6. Indeed, a leaner combustion is slower and the pressure peak is less important [3]. Even if the combustion curves related to different repetitions are not identical, they coincide pretty well to the same value after the combustion peak has been reached. Thanks to the pressure curve, it is possible to estimate the ignition delay: the values are 37 ms in fig. 5 and 35 ms in fig. 6. It also makes possible to estimate the duration of combustion: the results give, 237 ms in fig.5 and 122 ms in fig. 6. For this difference in combustion conditions, the ignition times are little influenced, however a significant difference is observed for the combustion time.

3.4. Dual-Fuel combustion

According to the idea of the dual fuel combustion, also as mentioned in the introduction, and thanks to the previous tests, we are able to obtain a fairly reproducible first combustion. Referring to fig. 7 showing the evolution of the pressure versus time, when we carry out the tests, we check the value of the pressure peak of the first combustion: it is decreasing slowly till an expected value around 20 barg. Then to validate a test, we check that the second injection of methane is done around those 20 barg to respect the injection ratio. Secondly, we check that the diesel injection is carried out between 15 and 18 bar. Fig. 7 is a typical one acquired obtained for a dual fuel combustion obtained thanks to the experimental system implemented, but only the pressure, trigger spark and gas injector signal were recovered from a test: the other curves are estimated in order to properly visualize and understand how events occur.

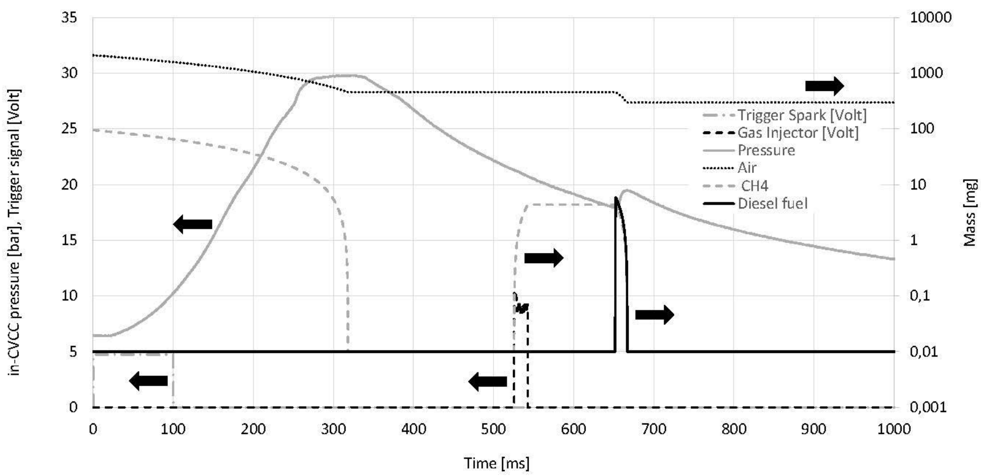

Figure 7 : Pressure, methane and air behaviour during DF Combustion.

Analysis with ignition delay and combustion duration

To calculate the ignition times and combustion duration, the signal is smoothed by Savitzky-Golay filter. The pressure delta is considered between the lowest value before combustion and the highest value after the combustion, which is the maximum at the pressure peak. To calculate the ignition times, 10% of the pressure difference is added to the minimum pressure value. The ignition time starts at the first edge of the injector shape-in signal and ends at 10% of the peak. With the same reasoning, the combustion time is considered between 10% and 90%.
The results give, although relatively constant, a tendency. It can generally be observed for ignition times to be low when there is only diesel or when the combustion lamdba is low and increases between the two situations. We can imagine that the methane in the chamber increases the ignition time of the diesel but as we approach a stoechiometric ratio, even if the amount of methane in the chamber is higher, the ignition is faster. The opposite trend is visible for the combustion time.

Split injection

According to this article [14], when combustion is lean, there is little or no combustion in the centre of the combustion chamber. In order to reduce the number of unburned parts, an injection separation approach is considered. To keep the same basis of comparison, the mass of diesel introduced into the combustion chamber must be the same.

Analysis with high-speed camera
To have a better optical control of the combustion, a camera with a high image rate is required. The camera used is the Memrecam GX-1f, it is equipped with a Sigma DG macro hsm 105 mm f/2.8 lens.

Heat Release Rate (HRR)
Another method is the comparison of the heat released. To do this, we first calculate an estimate of the heat released rate (HRR) with the equation (1). Then we calculate the integral of this function to obtain the sum of the energy released.

$$HHR(t) = \frac{1}{\gamma - 1} \times V \times \frac{dp}{dt} \qquad (1)$$

Where, γ is the mixture-specific ratio, V is the volume of the chamber and p the pressure inside.

For the calculation of the released heat, the integral should start at the beginning of the peak variation and end at the top of this peak. However, in the case of split injection, the peaks of variation are not so well defined. Moreover, since the second combustion takes place on the decreasing curve of the first combustion, it is difficult to know exactly where the combustion stops. For these two reasons, the total positive air is then taken into account for both cases. This no longer accurately represents the definition of the heat released by combustion but the comparison method is similar for both injection methods, so a proportional comparison can be made.

In both cases analysed, the simple injection releases more heat than the split injection. The peak variation is also more drawn and stable. In some results, there may even be a third peak of variation between the two injections, which is a sign of unstable combustion.

Region of combustion
The purpose of this method is to quantitatively compare the brightness of a given region in the chamber during combustion. Using image processing software, a black and white combustion image is cut into different disks/rings of different radius, each disk/rings are analysed separately. The average brightness of the images is then recovered and compared with an equivalent part of another combustion. This method should highlight the location of combustion in the chamber. Cutting is important because a simple injection combustion could be brighter overall than a split injection combustion, but with a different distribution. This method should allow to highlight which method permit to better burn the centre of the chamber.

But from one test to another for the same conditions, the combustion aspect can be very different, making the comparison sensitive to the operator's choice. These conditions do not allow for a relevant and reliable combustion analysis. The method itself makes sense, but first it is necessary to obtain a second combustion, which more reproducible to be able to use it.

Second combustion pressure curve isolation
To analyse the second combustion, it is important to take into account only the pressure variation due to it. To do this, it would be necessary to subtract the same pressure curve from the obtained pressure curve without the event of the second combustion. To do this, several methods have been developed: subtraction by a pressure curve from first combustion test and subtraction by cutting of the second combustion estimated by a trend curve. Unfortunately, none of these methods has given sufficiently satisfactory results.

4. Limits and improvements

4.1. Limits

Engine-like condition
It is important to realize that the reproduction of engine-like condition in a constant volume combustion chamber is not really ideal: induction swirl and squish compression are unfortunately not reproduced. Concerns about non-homogeneity are then present as it has been observed when the pilot injection of diesel is too close to that of methane.

Diesel injector
In order to reproduce a condition similar to a low load engine, the diesel injector must be used at low pressure (500 bar) and with a relatively low energizing time (ET) (250 µs). Under these conditions, the behaviour of the diesel injector is certainly not negligibly less stable. The vaporization, homogeneity of the sprays and the mass of diesel injected into the chamber may vary from time to time despite similar conditions. This variation in behaviour results in significantly different combustions. To analyse the results, a single test of each condition cannot be chosen. The choice of test would directly influence the result, which goes against the scientific approach. However, by taking several tests, the dispersion of the results may be large enough to make it difficult to draw conclusions.

Brightness of combustion
Although too fast to deduce anything, combustion is generally visible to the naked eye. It is generally possible to observe whether or not combustion has taken place.

To analyse what is happening, it is necessary to use a high-speed camera. Thanks to this camera, it is possible to differentiate between the two combustion events in split injection, which is impossible for the naked eye. On the other hand, the speed of image capture being high, it is necessary to have a minimum of brightness. This is where the limits of the system are: for leaner combustions, the brightness of the combustions are lower. The rendering of the image is then sometimes unusable despite the techniques of highlighting thanks to post-processing.

4.2. Improvements

Spline method

In order to properly analyse the results obtained, it is necessary to isolate the contribution of the second combustion and to do so to subtract a curve identical to that obtained by combining the two combustion events, but not containing the second combustion: this last part is removed from the curve and must be replaced by a curve that would follow the natural decrease in pressure without second combustion. This approach to more accurately reconstruct the natural curve than a polynomial approach, is the spline approach. Indeed, splines have the advantage of being able to easily adjust to the curve thanks to the crossing points and tangents.

*Chemiluminescence OH**

Since the normal high-speed camera does not always give good results because of the low brightness of some combustions, the OH* chemiluminescence image method will be used. The setup consists of a high-speed camera, a UV lens and a narrow-band spectral filter. With this method it is hoped to be able to observe the combustion that was not well visible with it based only on the visible spectrum.

5. Conclusion

The purpose of this work was to develop a test rig for a constant-volume combustion chamber in order to characterize ignition and combustion phenomena in the context of dual-fuel combustion with diesel and methane. An installation was already existing thanks to previous works. Research to improve and control it has therefore been carried out.

A leak analysis showed that the combustion chamber resists a pressure of 30 barg and even slightly more for short events such as combustion. Therefore, despite high pressure leaks, the leaks can be neglected for short duration events and the installation can be considered as adequate for testing for this pressure range. Tests on the characterization of the methane injector were conducted to control the amount of methane introduced into the combustion chamber according to the injection conditions. The characterization seems to give satisfactory results. After the tests, the injector is acceptably characterised: the objectives have been achieved. A key point of this work is to obtain a controlled and reproducible first combustion in order to be able to initiate the second combustion, dual fuel, under similar engine-like conditions between each test.

A high-speed camera helped to understand some phenomena but is still limited in the analysis of results mainly due to the poor brightness of images. Post-processing and analysis tools have been developed and results obtained. The results obtained so far do not allow many new conclusions to be drawn on a more in-depth understanding of dual-fuel ignition and combustion phenomena. Nevertheless, the test rig can be considered as functional. It is not perfect, but with the means deployed, future tests with new methods and the current control of the test rig give hope for interesting results.

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